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# Optimum Design of Power Converter Current Controllers in Large-Scale Power Electronics Based Power Systems

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**Abstract**—In a large-scale power electronic system like a wind farm, the mutual interactions between the power converter controllers and passive components may lead to instability problems or undesired dynamic response. This paper presents an optimum parameter design procedure for the power converter controllers in a power electronic system in order to guarantee a stable operation and to guarantee an acceptable dynamic response. In the approach, first, all oscillatory modes are calculated by a Multi-Input Multi-Output (MIMO) transfer function matrix of the power system; then, a multi-objective optimization procedure based on the Genetic Algorithm (GA) is presented to place the modes in the desired locations in order to increase the stability margin and to improve the dynamic response. Time-domain simulations of a 400-MW wind farm in the PSCAD/EMTDC environment confirms the effectiveness of the presented design approach.

**Keywords**—power electronic system, grid-connected converters, stability, dynamic response, design, optimization, damping

## I. INTRODUCTION

The fast growth of renewable energy sources, HVDC systems, variable-speed drivers, etc., has brought concerns about the stable and reliable operation of the future power system [1]-[6]. A power electronic system containing many power converters may show an undesired dynamic behavior or even an unstable operation, while the individual power converters show an acceptable dynamic characteristic for a strong grid. Recently, Transmission System Operators (TSOs) in different countries have reported a few times that they could not connect a wind farm to the grid because of harmonic-frequency oscillations [7]. In such cases, individual wind turbines have already passed different tests but the whole wind farm does not show a stable operation. The dynamic oscillations above the fundamental frequency are mainly coming from the mutual interactions between the high-bandwidth controllers and the passive components of the system [8], [9]. Therefore, this paper presents a method for designing the power converters to reduce the electrical oscillations by considering some information of the power system. There are two general approaches to analyze a power electronic system: One is the non-linear time-domain simulation analysis, which is accurate in a wide frequency range but has high computational burden. The second approach is the linearized frequency-domain analysis, which is accurate in the intended frequency range and

has low computational burden [10], [11]. Optimization of a large-scale power electronic system in the time-domain is complex because of too high computational burden. So far, frequency-domain analysis based on the state-space modeling has been done in various power electronic systems like microgrids, current source converters, and parallel voltage source inverters [12]-[16]. However, the state-space modeling can be complex for large-scale power electronic systems because it needs the information of each component of the system in details [17]-[21]. Another tool, for dynamic analysis of the system in the frequency-domain, is the impedance based modeling [22]-[27]. In this method, the source output impedance ( $Z_s$ ) and the load input impedance ( $Z_l$ ) are obtained and then the interconnected system stability is assessed by the Nyquist criterion of the ratio of  $Z_l(s)/Z_s(s)$  [22]-[27]. Therefore, it can just identify if the system is stable and can not identify how much the stability margin is. So, the impedance-based analysis can not be used as a powerful design tool for a large number of power converters in a large-scale power electronic system.

In order to reduce the electrical oscillations and to improve the dynamic response in a large power electronic system, this paper presents a frequency-domain based optimum design method, which is simple and has low computational burden. The proposed optimized design approach is solved by using Genetic Algorithm (GA) and its objective function is to increase the stability margin and to improve the dynamic response. A large-scale power electronics based system is introduced as a Multi-Input Multi-Output (MIMO) transfer function matrix, which is simpler than state-space modeling. The dynamic analysis, the damping and frequencies of oscillatory modes are identified based on the determinant of the MIMO matrix.

In Section II, a grid-connected power electronic converter is modeled by a Norton equivalent circuit, i.e., a current source with a parallel active admittance. In Section III, a large power electronic system is modeled by a MIMO transfer function matrix. The proposed optimized parameter design is explained in Section IV, where the oscillatory modes of the system are placed in desired locations. In Section IV, a 400-MW wind farm is considered as a case study. In Section V, the proposed optimum design is tested by time-domain simulations of the 400-MW wind farm studied using the PSCAD/EMTDC

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environment software.

## II. ADMITTANCE MODEL OF GRID-CONNECTED CONVERTER

A simple block-diagram of a grid-connected converter with an inner control loop is shown in Fig. 1(a), where  $G_{cont-k}$  is the current controller, and  $G_{delay-k}$  is the delay of the digital control implementation. Fig. 1(b) shows the block-diagram of the current closed-loop control system, where the PoC voltage ( $V_{PoC-k}$ ) and the current reference ( $I_{ref-k}$ ) are the inputs and the grid current ( $I_{g-k}$ ) is the output. From Fig. 1(b), the grid current can be obtained from

$$I_{g-k} = G_{c-k} I_{ref-k} - Y_{c-k} V_{PoC-k} \quad (1)$$

where  $G_{c-k}$  and  $Y_{c-k}$  are

$$G_{c-k} = \frac{T_{c-k}}{1 + T_{c-k}}, Y_{c-k} = \frac{Y_{Lf-k}}{1 + T_{c-k}} \quad (2)$$

$T_{c-k}$  and  $Y_{Lf-k}$  are

$$T_{c-k} = G_{cont-k} G_{delay-k} Y_{Lf-k}, Y_{Lf-k} = \frac{1}{sL_{f-k}} \quad (3)$$

Based on Equation (1), a grid-connected converter can be modeled by an ideal current source along with a parallel active admittance (Norton equivalent circuit) as shown in Fig. 1(c). This paper focuses on optimum design of the current controller, which is fast and a high-bandwidth controller. Therefore, the outer power controllers and grid synchronization loops are neglected as they are too slow to have influence on current controller dynamics. In this paper,  $G_{cont-k}$  is considered to be a Proportional plus Resonant (PR) current controller and  $G_{delay-k}$  is modeled by Pade approximation, i.e.,

$$G_{cont-k} = K_{p-k} + \frac{K_{i-k}s}{s^2 + \omega_f^2} \quad (4)$$

$$G_{delay-k}(s) = e^{-1.5T_{s-k}s} \approx \frac{1 - \frac{1.5T_{s-k}}{2}s + \frac{(1.5T_{s-k})^2}{12}s^2}{1 + \frac{1.5T_{s-k}}{2}s + \frac{(1.5T_{s-k})^2}{12}s^2}$$

where  $\omega_f$  is the fundamental frequency and  $T_{s-k}$  is the sampling period of the digital control.

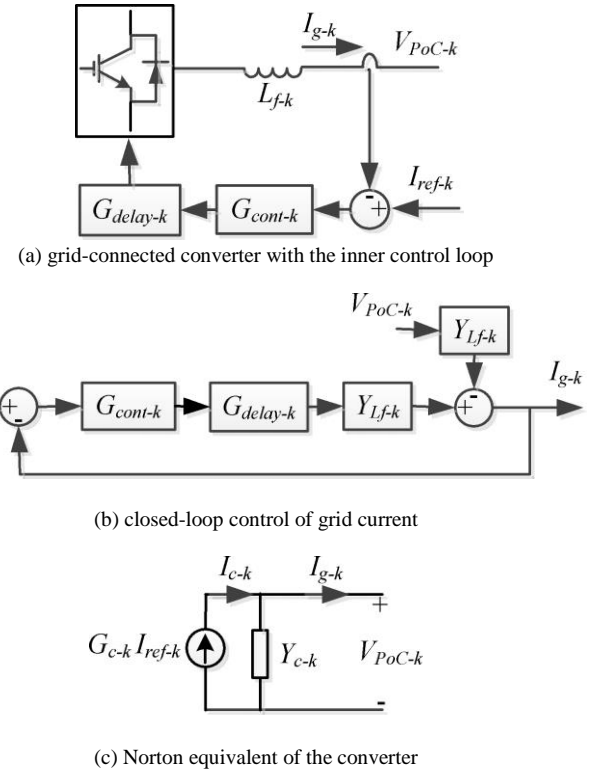


Fig. 1. Grid-connected converter with the inner control loop and its equivalent circuit.

## III. A POWER ELECTRONIC SYSTEM AS A MULTI-INPUT MULTI-OUTPUT (MIMO) TRANSFER FUNCTION MATRIX

By modeling of every passive element and active element (power electronic converters) as Norton equivalent circuit, the current-voltage relationships in a power electronic system can be obtained by the nodal admittance matrix as given in (5). In (5), it is assumed that bus 1 is connected to the electrical grid and bus 2 to bus  $n+1$  are connected to the power electronic converters.  $Y_{c-k}$  ( $k=1, 2, \dots, n$ ),  $Y_{ij}$ ,  $Y_{ij}(s)$  ( $i, j=1, 2, \dots, m$ , and  $i \neq j$ ) are the active admittance of the  $k^{th}$  power electronic converter, the connected admittance to the  $i^{th}$  bus, the admittance between  $i^{th}$  bus and  $j^{th}$  bus, respectively. When a component model is black-box, its equivalent admittance can be obtained by

$$\begin{bmatrix} I_g \\ I_{c-1} \\ I_{c-2} \\ \vdots \\ I_{c-n} \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{11} & -Y_{12} & -Y_{13} & \cdots & -Y_{1(n+1)} & -Y_{1(n+2)} & \cdots & -Y_{1m} \\ -Y_{21} & Y_{22} + Y_{c-1} & -Y_{23} & \cdots & -Y_{2(n+1)} & -Y_{2(n+2)} & \cdots & -Y_{2m} \\ -Y_{31} & -Y_{32} & Y_{33} + Y_{c-2} & \cdots & -Y_{3(n+1)} & -Y_{3(n+2)} & \cdots & -Y_{3m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ -Y_{(n+1)1} & -Y_{(n+1)2} & -Y_{(n+1)3} & \cdots & Y_{(n+1)(n+1)} + Y_{c-n} & Y_{(n+1)(n+2)} & \cdots & -Y_{(n+1)m} \\ -Y_{(n+2)1} & -Y_{(n+2)2} & -Y_{(n+2)3} & \cdots & -Y_{(n+2)(n+1)} & Y_{(n+2)(n+2)} & \cdots & -Y_{(n+2)m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ -Y_{m1} & -Y_{m2} & -Y_{m3} & \cdots & -Y_{mn} & -Y_{m(n+2)} & \cdots & Y_{mm} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \vdots \\ V_n \\ V_{(n+1)} \\ \vdots \\ V_m \end{bmatrix} \quad (5)$$

experiment (if the component has been built) or by numerical simulations (if the component has been designed but has not been built yet). Equation (5) is actually a Multi-Input Multi-Output (MIMO) transfer function matrix [28], where the outputs are the bus voltages and the inputs are the injected currents, i.e.,

$$\mathbf{V}(s) = \mathbf{G}(s)^{-1} \mathbf{I}(s) \quad (6)$$

The poles of the introduced MIMO transfer function can be calculated by solving the following equation:

$$\det[\mathbf{G}(s)] = 0$$

$$\Rightarrow p_1 = \alpha_1 + j\beta_1, p_2 = \alpha_2 + j\beta_2, \dots, p_q = \alpha_q + j\beta_q \quad (7)$$

where the frequency ( $f_i$ ) and the damping ratio ( $\zeta_i$ ) of the poles can be obtained from

$$f_i = \frac{\beta_i}{2\pi} \quad \zeta_i = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \beta_i^2}} \quad (8)$$

The poles of the MIMO transfer function matrix basically are the poles of its elements, i.e.,

$$G_{ij}(s) = \frac{P(s)}{(s-p_1)(s-p_2)\dots(s-p_q)}$$

$$= \frac{A_1}{(s-p_1)} + \frac{A_2}{(s-p_2)} + \dots + \frac{A_q}{(s-p_q)} \quad (9)$$

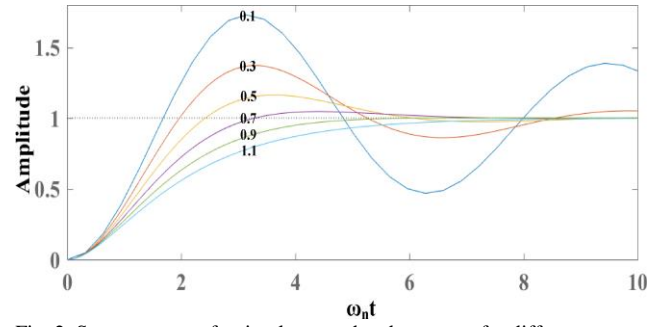


Fig. 2. Step response of a simple second-order system for different damping ratios.

The inverse Laplace transform of  $G_{ij}(s)$  is

$$G_{ij}(t) = A_1 e^{p_1 t} + A_2 e^{p_2 t} + \dots + A_q e^{p_q t}$$

$$= A_1 e^{\alpha_1 t} e^{j\beta_1 t} + A_2 e^{\alpha_2 t} e^{j\beta_2 t} + \dots + A_q e^{\alpha_q t} e^{j\beta_q t} \quad (10)$$

Therefore, the poles of  $G_{ij}(s)$  in the s-domain are related to the oscillations of the system in the time-domain. The imaginary parts of the poles identify the frequencies of oscillations and the real parts identify the damping of the oscillations. If  $\alpha_q$  (one of the real parts) is positive, the term  $A_q e^{\alpha_q t} e^{j\beta_q t}$  is a function with an increasing exponential magnitude and the system is unstable. If  $\alpha_q$  is negative, the term  $A_q e^{\alpha_q t} e^{j\beta_q t}$  is a decaying exponential function with a final value of zero.

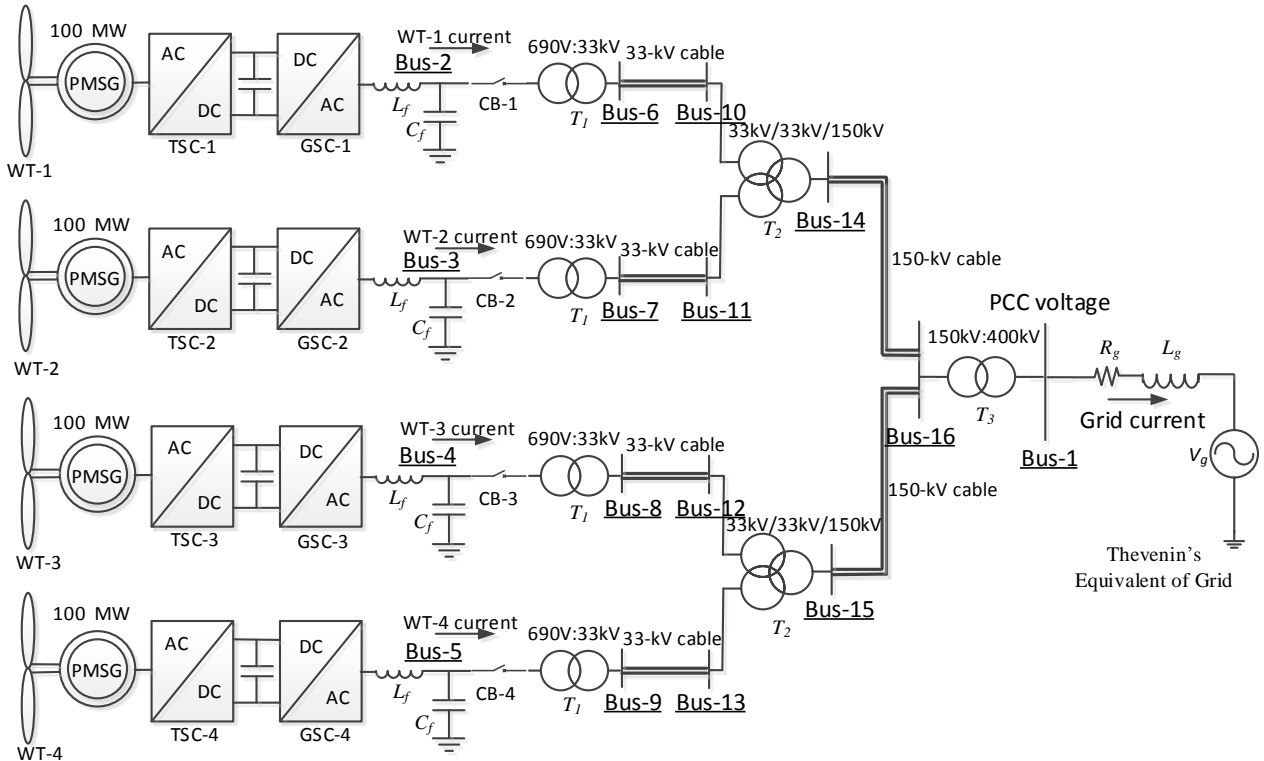


Fig. 3. 400-MW wind farm, which is studied for the proposed optimum controller design method.

#### IV. PROPOSED OPTIMUM DESIGN OF CURRENT CONTROLLER

##### A. Guaranteeing stability

According to the previous discussion, a power electronics based system is stable if and only if all its poles ( $P_1, P_2, \dots$ , and  $P_q$ ) have negative real parts. The mode with the largest real part can be found by

$$P_c = \alpha_c + j\beta_c \quad \alpha_c = \text{Max}(\alpha_1, \alpha_2, \dots, \alpha_q) \quad (11)$$

If  $P_c$  has a negative real part, it means that the real parts of all modes are negative. Therefore, in order to guarantee the stability, an inequality constraint,  $H(\mathbf{x})$ , is considered in GA algorithm to set the real part of  $P_c$  smaller than zero. The threshold value for stability is zero mathematically. However, because of the round-off errors of floating-point computations and the grid variations, the threshold value should be considered a value larger than zero to be robust. So, it is considered to be ten here., i.e.,

$$\alpha_c + 10 = H(\mathbf{x}) \leq 0 \quad (12)$$

where  $\mathbf{x}$ , optimization variable, can be a vector including the current controller and filter parameters of the grid-connected converter.

$$\mathbf{x} = [K_p, K_i, L_f, C_f] \quad (13)$$

The optimum parameter vector ( $\mathbf{x}$ ) includes the filter parameters to have more freedom degrees and to optimize the system ideally. In a case, if the filter parameters can not be redesigned, the vector includes only the controller parameters. In this case, there are less freedom degrees for the optimization and may not optimize the system ideally.

##### B. Guaranteeing the desired dynamic performance

Fig. 2 shows the step response of a simple second-order system for different damping ratios, which is used as an example for evaluating the dynamic response of a system. Fig. 2 shows that the amount of overshoot depends on the damping ratio. The system with a smaller damping ratio reaches the final value faster, but the response oscillates around this final value. A system with a damping ratio around 0.8 can be a good trade-off between the speed and oscillation of the response as shown in Fig. 2.

In a power electronics based systems, low-frequency modes are related to the power converter controllers and the high-frequency modes are more related to the cables and transformers. As the switching frequency ( $f_s$ ) is considered to be 2.5 kHz, the maximum logical bandwidth for the current controller would be around 500 Hz ( $f_s/5$ ) [29]. Therefore, In order to guarantee the desired dynamic performance of the power converters in a power electronic system, an objective function is considered to set the damping ratios of all low-frequency modes close to 0.8; in fact, the objective function is to minimize  $F(\mathbf{x})$  as described in (14).

$$F(\mathbf{x}) = \text{Max}[\zeta_1 - 0.8, \zeta_2 - 0.8, \dots, \zeta_n - 0.8]$$

$$\zeta_j = \frac{-\alpha_j}{\sqrt{\alpha_j^2 + \beta_j^2}}, f_j = \frac{\beta_j}{2\pi} < f_{h1} \cong 500\text{Hz}, j = 1, 2, \dots, n \quad (14)$$

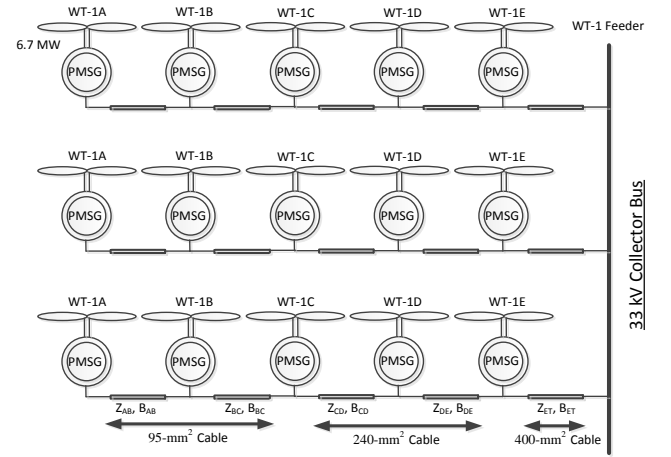


Fig. 4. Fifteen wind turbines, which are located on each 100-MW string of the wind farm shown in Fig. 3.

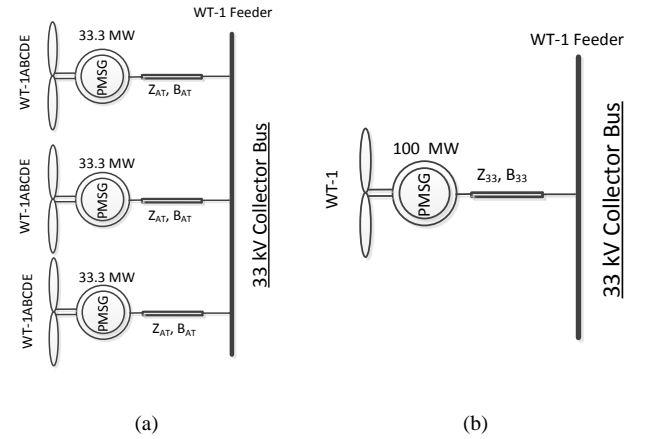


Fig. 5. Aggregated model of the fifteen wind turbines shown in Fig. 4, (a) aggregated model on each feeder, (b) aggregated model of three feeders.

#### V. A 400-MW WIND FARM AS A CASE STUDY

The effectiveness of the proposed optimized design approach is studied for a 400-MW wind farm with 100-MW aggregated strings, as shown in Fig. 3. Fifteen Wind Turbines (WTs) of 6.7 MW are located on three parallel feeders as shown in Fig. 4.

Under the nominal operation, the current on the feeder is increasing towards the collector bus as the number of the WTs is also increasing. Therefore, a closer cable to the collector bus should have larger cross-section than a farther cable. Consequently, three different cables (95 mm² cable, 240 mm² cable, and 400 mm² cable) carry the feeder current. Five WTs of 6.7-MW on each feeder can be aggregated by one 33-MW WT as shown in Fig. 5(a). If it is assumed that the injected power by the WTs on the feeder are the same, the equivalent impedance parameters of the 33-MW WT can be calculated by

$$Z_{AT} = \frac{Z_{AB} + 4Z_{BC} + 9Z_{CD} + 16Z_{DE} + 25Z_{ET}}{25} \quad (15)$$

$$B_{AT} = B_{AB} + B_{BC} + B_{CD} + B_{DE} + B_{ET}$$

where,  $Z_{AT}$  and  $B_{AT}$  are the equivalent series impedance and the equivalent shunt susceptance, respectively.  $Z_{AB}$ ,  $Z_{BC}$ ,  $Z_{CD}$ ,

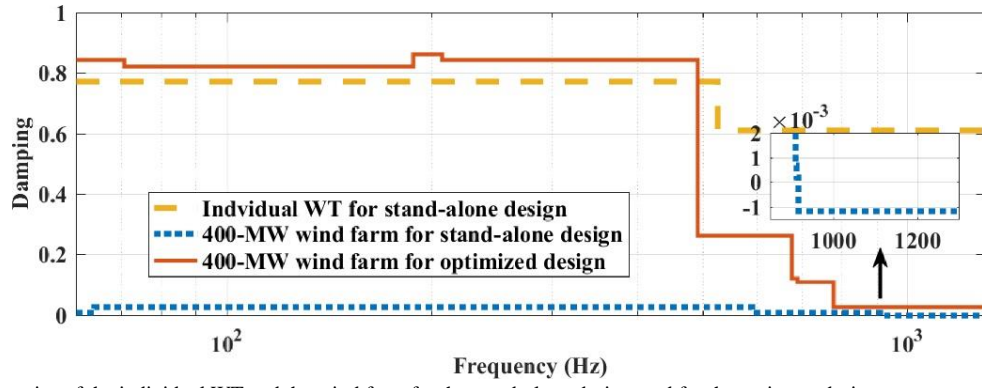


Fig. 7. Mode damping ratios of the individual WT and the wind farm for the stand-alone design, and for the optimum design.

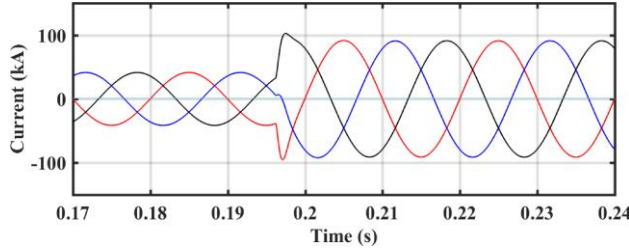


Fig. 6. Step-response of the designed GSC for a strong grid.

Table I. Parameters of the 400-MW wind farm and Genetic Algorithm (GA) Solver

Parameter		Value
Transformer T <sub>1</sub>	Leakage inductance	1.378 $\mu$ H
	Shunt capacitance	3.24 $\mu$ F
Cable 33-kV	Series inductance	0.436 mH
	Series resistance	0.0537 $\Omega$
	Leakage inductance	1.891 mH
Transformer T <sub>2</sub>	Shunt capacitance	0.26 $\mu$ F/km
	Series inductance	0.5 mH/km
Cable 150-kV (Cable length = 10 km)	Series resistance	0.0574 $\Omega$ /km
	Leakage inductance	22.788 mH
	Shunt capacitance	0.0574 $\mu$ F/km
Transformer T <sub>3</sub>	Leakage inductance	22.788 mH
	Shunt capacitance	0.0574 $\mu$ F/km
Grid	X/R ratio	20
	SCR	100
Current controller	K <sub>p</sub>	2.5e-3
	K <sub>i</sub>	2
	f <sub>s</sub>	2.5 kHz
Genetic Algorithm (GA) Solver	Population Size	40
	Generations	160
	Stall Generations	80
	Function Tolerance	1 $\times 10^{-5}$

$Z_{DE}$ , and  $Z_{ET}$  are the series impedances of the sections and  $B_{AB}$ ,  $B_{BC}$ ,  $B_{CD}$ ,  $B_{DE}$ , and  $B_{ET}$  are the shunt susceptances (see Fig. 4). Finally, the aggregated 33.3-MW WTs on three parallel feeders can be aggregated as one 100-MW WT (see Fig. 5(b)). The equivalent series impedance and shunt susceptance can be calculated by

$$Z_{33} = \frac{Z_{AT}}{3} \quad B_{33} = 3B_{AT} \quad (16)$$

Since the dc-link is almost constant, the dynamics of the Turbine-Side Converters (TSCs) can be neglected. A simple Thévenin equivalent voltage source is used to represent the grid. The transformers are modeled by its short-circuit impedances and the cables are modeled by the nominal  $\pi$ -

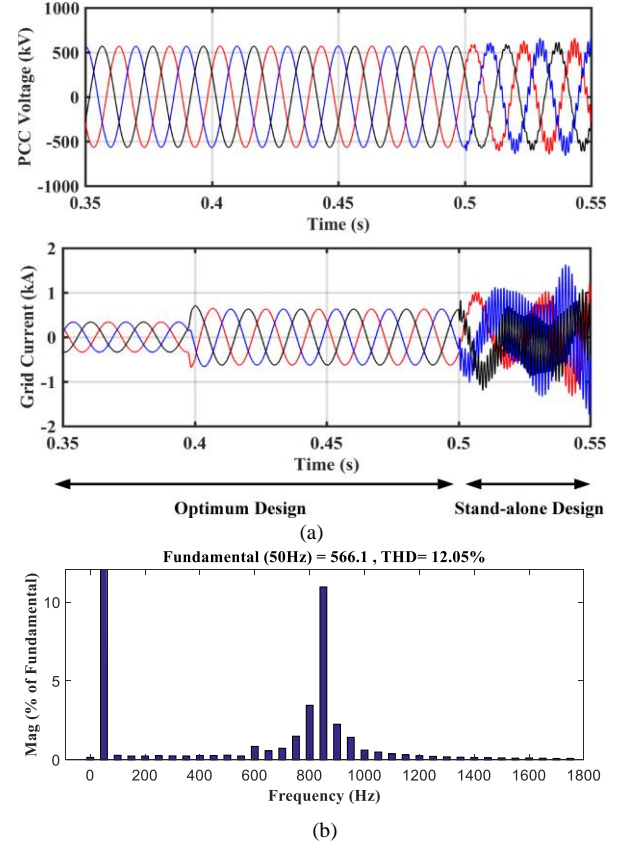


Fig. 8. Dynamic response of GSC. GSC parameters are changed from the optimum design to the initial design at  $t = 0.5$  s and the dynamic response of the optimum design is also tested at  $t = 0.4$  s, (a) PCC voltage and grid current, (b) FFT analysis of PCC voltage between  $t = 0.52$  s to  $t = 0.54$  s.

model. The parameters of the wind farm are given in Table I. Short Circuit Ratio (SCR) is defined by

$$SCR = \frac{V_g^2}{Z_g S_{base}} \quad (17)$$

Where  $V_g$  and  $Z_g$  are the grid voltage and the grid impedance, and  $S_{base}$  is the apparent power injected by the wind farm. For large X/R ratio,  $Z_g = X_g = \omega L_g$ . More detailed information about the model can be found in [29]. The current controller and filter parameters of the Grid-Side Converters (GSCs) are



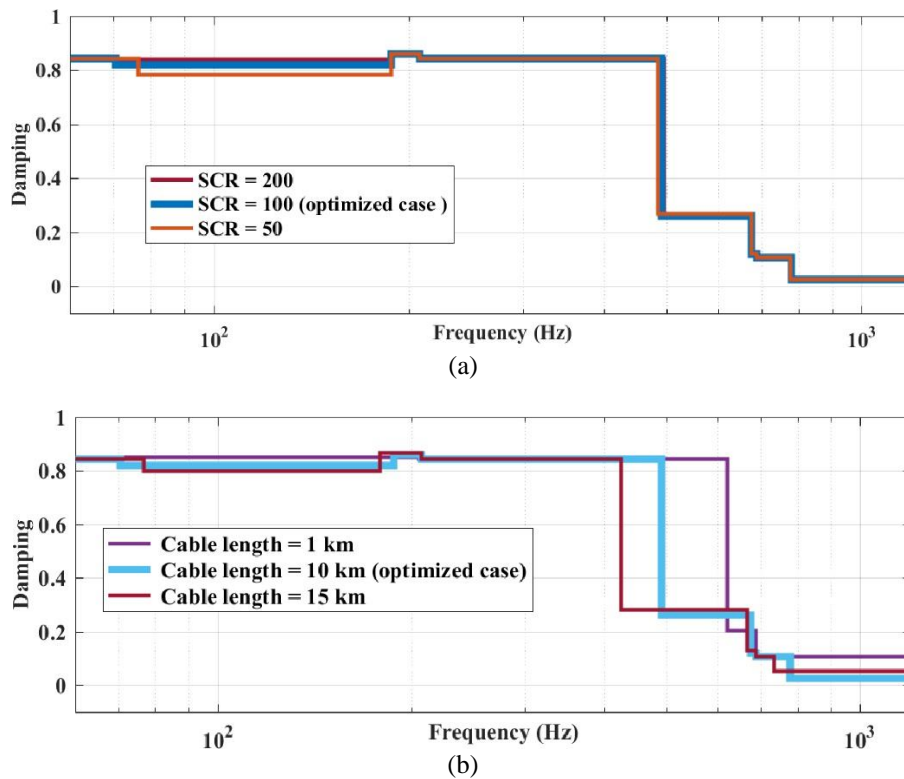


Fig. 9. Robustness of the optimum design case (SCR = 100 and Cable length = 10 km) against variations, (a) SCR = 100 (optimized case) is changed to SCR = 50 and SCR = 200, (b) Cable length = 10 km (optimized case) is changed to Cable length = 1 km and Cable length = 15 km.

designed for a desired phase-margin of  $45^\circ$  for stand-alone operation. Fig. 6 shows the step-response of the GSC for a strong grid, where a desired dynamic response can be observed. The same controllers are used for all GSCs.

## VI. PROPOSED OPTIMUM DESIGN IN FREQUENCY-DOMAIN AND CORRESPONDING TIME-DOMAIN SIMULATIONS

### A. Optimum design

Fig. 7 shows the mode damping ratios of the individual WT and the wind farm for the stand-alone design (initial design). The damping ratios of the modes of the wind farm for the optimized parameters ( $K_p = 9.51 \times 10^{-3}$ ,  $K_i = 4.16$ , and  $f_{res} = 357$  Hz) are also shown in Fig. 7. As it can be seen, the damping ratios of the individual WT for the stand-alone design is around 0.8, which confirms that the individual WT for a strong grid has a good stability margin and an acceptable dynamic response. However, when all WTs are connected to the wind farm, the damping ratios for low-frequency modes are too small and the damping ratio for frequency around 900 Hz is negative, which shows that the wind farm is unstable around this frequency. Therefore, it is necessary to redesign the controller parameters to improve the stability margin and to guarantee a desired dynamic response. As shown in Fig. 7, after setting the GSC parameters based on the proposed optimum design procedure, all modes have positive damping, which confirms that the wind farm has a stable operation. In addition, the low-frequency modes, which is related to the power converter dynamics, have suitable dampings around 0.8, which depicts that the wind farm has a desired dynamic performance for the optimum design.

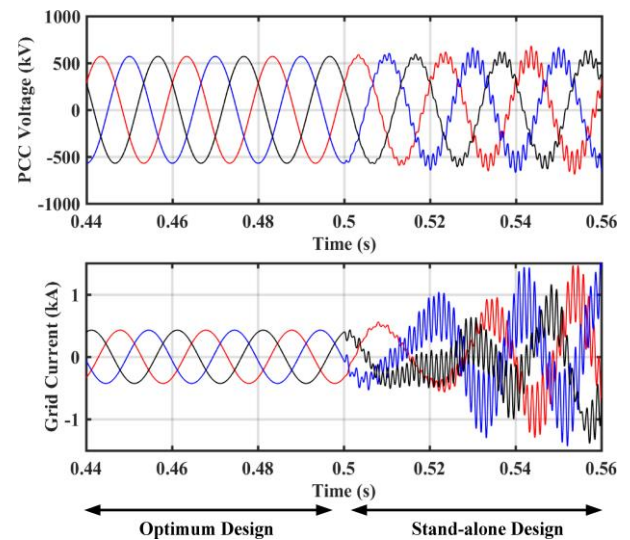


Fig. 10. Robustness of the optimum design. The GSC parameters are optimized and set for SCR = 100 and Cable length = 10 km but the wind farm is simulated for another case, i.e., SCR = 50 and Cable length = 15 km. At  $t = 0.5$ , the GSC parameters are changed to the initial design

In Fig. 8, the wind farm is simulated in the time-domain using PSCAD software, where the current controller parameters of the GSCs have been set by the proposed optimum design (before  $t = 0.5$  s). At  $t = 0.4$  s, the current reference is changed from 0.25 p.u. to 1 p.u. As it can be seen, the wind farm has a good dynamic response and a stable operation for the optimized parameters. At  $t = 0.5$ , the GSC parameters are changed from the optimum design to the initial design. As shown in Fig. 8,

some oscillations around 900 Hz propagate into the wind farm, because of the instability problems as predicted in Fig. 7 in the frequency-domain. Therefore, it can be concluded that a good control design for an individual power converter cannot guarantee the stable operation of the whole power electronics based system as shown in Fig. 8.

### B. Sensitivity analysis with respect to system variations

In this section, the robustness of the optimum design case (SCR = 100 and Cable length = 10 km) against variations of the wind farm is studied. Fig. 9(a) shows the mode damping ratios of the wind farm, where SCR = 100 (optimized case) is changed to SCR = 50 and SCR = 200. Fig. 9(b) shows the mode damping ratios, where Cable length = 10 km (optimized case) is changed to Cable length = 1 km and Cable length = 15 km. As it can be seen, the damping ratios of modes, particularly low-frequency modes, are not affected a lot against such variations. The high frequency poles are related to the resonance modes resulting from the capacitance and the inductance of the cables. By increasing the cable length, the capacitance and the inductance of the cable increase and the resonance frequency decreases. The damping of these poles is corresponded to the resistance of the cable. As this resistance is very small, the damping of these poles is small. In order to confirm the robustness of the optimized design, the time-domain simulations have also been performed. First, the GSC parameters are optimized and set for SCR = 100 and Cable length = 10 km. However, the wind farm is simulated for another SCR and cable lengths, i.e., SCR = 50 and Cable length = 15 km. At  $t = 0.5$ , the parameters are changed to the initial design. As it can be seen from Fig. 10, the wind farm with the optimum controller design presents a robust and stable operation. However, after  $t = 0.5$ , the wind farm with the initial parameters is unstable and harmonic-frequency oscillations propagate into the grid.

## VII. CONCLUSION

This paper presents a multi-objective design procedure for the power converter controllers in order to increase the stability margin in a power electronics based system. A power electronic system is introduced as a Multi-Input Multi-Output (MIMO) transfer function matrix and the oscillatory modes are identified by the determinant of the MIMO matrix. The proposed algorithm put the modes in the desired locations to improve the dynamic response of the system. A 400-MW wind farm is studied as a power electronics based system for the proposed optimum design procedure. Time-domain simulations confirm that a good design for an individual converter under strong grid cannot guarantee a stable operation of the whole power electronic system including many other converters and passive components. On the other hand, the proposed design technique is a powerful tool to analyze and to improve the dynamic performance of a large-scale power electronic system like a wind farm. In addition, the power electronic system with the optimum controller design shows a robust and stable operation against variations of the system.

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